Nuclear disintegration induced by virtual photons at heavy-ion colliders

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Abstract

A model of electromagnetic interaction of relativistic heavy ions which makes it possible to calculate the inclusive and exclusive characteristics of such interactions is presented. The multistep model includes (1) the single and double virtual photon absorption by a nucleus, (2) intranuclear cascades of produced hadrons and (3) statistical decay of excited residual nuclei described by evaporation, fission and multifragmentation mechanisms. Components of the model were verified by comparison of calculation results with experimental data obtained with monoenergetic photons and heavy ions at KEK-Tanashi Synchrotron and CERN SPS accelerator, respectively.

1   Description of the model

The relativistic Coulomb excitation of nuclei is a well-known phenomenon [1]. It is expected to play an important role in collisions of ultrarelativistic heavy nuclei at new colliders, RHIC and LHC [2, 3]. The process may be described in the framework of the Weizsäcker-Williams method of equivalent photons. According to this method the impact of Lorentz-boosted Coulomb field of a nucleus on the collision partner may be treated as the absorption of equivalent photons. Due to the coherent nature of photon emission by the nucleus,

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such photons are almost real, $Q^2 \leq 1/R^2$, R is the nuclear radius. Therefore photonuclear reaction data obtained in experiments with real monoenergetic photons and appropriate theoretical models describing photonuclear reactions may be used to predict the properties of electromagnetic dissociation process.

Since an ultrarelativistic nucleus moving at the impact parameter b with the velocity $\beta = v/c \approx 1$, $(\gamma \gg 1)$ spends a short time Δt near the collision partner, the virtual photon spectrum contains all the frequencies up to the maximum energy $E_\gamma^{max} \sim 1/\Delta t \sim \gamma/R$:

$$N(E_\gamma, b) = \frac{\alpha Z_t^2}{\pi^2} \frac{\mathsf{x}^2}{\beta^2 E_\gamma b^2} \Big(K_1^2(\mathsf{x}) + \frac{1}{\gamma^2} K_0^2(\mathsf{x}) \Big), \tag{1}$$

where α is the fine structure constant, K_0 and K_1 are the modified Bessel functions and $\mathsf{x} = E_\gamma b/(\gamma\beta)$. The mean number of photons absorbed by the collision partner of mass A_p is defined by:

$$m(b) = \int_{E_\gamma^{min}}^{E_\gamma^{max}} N(E_\gamma, b)\sigma_{A_p}(E_\gamma)dE_\gamma, \tag{2}$$

where $\sigma_{A_p}(E_\gamma)$ is the appropriate total photoabsorption cross section obtained starting from the photoneutron threshold at $E_\gamma^{min} \sim 7$ MeV.

Assuming the Poison distribution for the multiphoton absorption with the mean multiplicity $m(b)$, Eq.(2), the integral cross sections are calculated for the first- and second-order processes [4] for a particular dissociation channel i:

$$\sigma_i^{(1)} = \int_{E_\gamma^{min}}^{E_\gamma^{max}} dE_1 N^{(1)}(E_1)\sigma_{A_p}(E_1)f_i^{(1)}(E_1), \tag{3}$$

$$\sigma_i^{(2)} = \int_{E_\gamma^{min}}^{E_\gamma^{max}} \int_{E_\gamma^{min}}^{E_\gamma^{max}} dE_1 dE_2 N^{(2)}(E_1, E_2)\sigma_{A_p}(E_1)\sigma_{A_p}(E_2)f_i^{(2)}(E_1, E_2), \tag{4}$$

with the following single and double photon spectral functions:

$$N^{(1)}(E_1) = 2\pi \int_{b_{min}}^{\infty} bdb e^{-m(b)} N(E_1, b),$$

$$N^{(2)}(E_1, E_2) = \pi \int_{b_{min}}^{\infty} bdb e^{-m(b)} N(E_1, b) N(E_2, b).$$

The values $f_i^{(1)}(E_1)$ and $f_i^{(2)}(E_1, E_2)$ defined as the branching ratios for the considered disintegration channel i in the single and double photon absorption, respectively, have to be calculated by our multistep model. Similar expressions may be written for the differential distributions of produced particles on the rapidity, transverse momentum and other variables.

In order to obtain $f_i^{(1)}$ and $f_i^{(2)}$ several mechanisms are included in a new Relativistic ELectromagnetic DISsociation (RELDIS) code for the Monte Carlo simulation, namely, the intranuclear cascade of fast particles produced after the photon absorption on a nucleon or nuclear pair [5], and the evaporation of nucleons and lightest fragments, binary fission or multifragmentation [6] at a later stage of interaction. The multifragmentation process dominates when the excitation energy of residual nucleus, $E^\star$, exceeds $3 - 4$ MeV/nucleon and is described by the statistical multifragmentation model (SMM) [6]. For fissile nuclei the evaporation may take place before or after the fission. The competition of evaporation and fission is also described with the SMM. The lightest fragments may be also created via coalescence of fast nucleons into d, t, ^{3}He or ^{4}He [7]. The decay of highly excited light residual nuclei with $A \leq 16$ is treated by the Fermi break-up mechanism [6]. Other details of the calculation scheme may be found in Refs. [4, 5, 8].

2 Emission of nucleons and lightest fragments

Depending on the photon energy, E_γ, and mass number, A_p, different processes take place in the nuclear photoabsorption. Due to the contributions of several mechanisms: $\gamma N \rightarrow \pi N$, $\gamma N \rightarrow 2\pi N$ and $\gamma(np) \rightarrow np$ the calculated double differential spectra $d^2\sigma/d\Omega dP$ of pions and protons have complex shapes above the pion production threshold [5]. The spectra of fast particles π^+, π^-, η and p predicted by the model were compared in Ref. [5] with available sets of experimental data at $140 \leq E_\gamma \leq 1000$ MeV including the data obtained with KEK-Tanashi, the 1.3-GeV Electron Synchrotron. A satisfactory description of the spectra was obtained.

Fast hadrons produced after the photon absorption initiate a cascade of subsequent collisions with the intranuclear nucleons leading to the heating of a residual nucleus. Later the nucleus undergoes de-excitation by means of the emission of nucleons and fragments. Because of a low Coulomb barrier in light nuclei the rates of proton and neutron emission are comparable.

Fragment spectra in the photoabsorption on a carbon nucleus are given

in Fig. 1. The low energy part of the deuteron spectra is explained by the explosive Fermi break-up while the high energy part is attributed to the coalescence mechanism. Since the main part of fast nucleons is emitted in the forward direction, the coalescence contribution dominates at small angles. On the contrary, the distribution of deuterons from Fermi break-up is nearly isotropic. Because of the option to accelerate also light oxygen ions at RHIC,
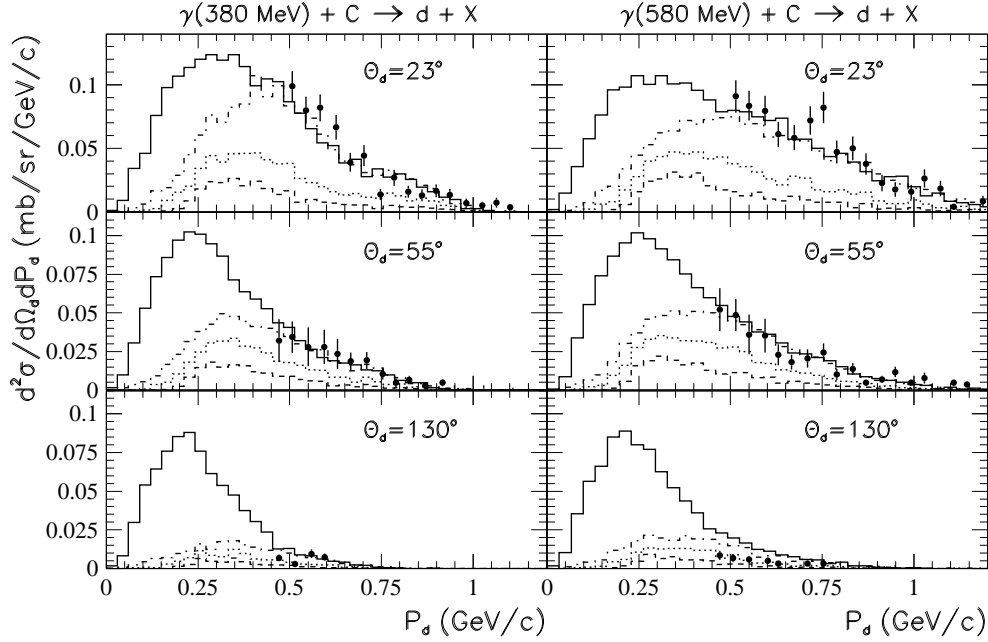

Figure 1: Deuteron emission in photoabsorption on carbon. Points: KEK-Tanashi data [9]. Solid histograms: results of the intranuclear cascade calculations with coalescence and Fermi break-up. Contributions from coalescence mechanism are shown by the dashed, dotted and dash-dotted histograms for different values of coalescence parameter [7]: $p_0 = 90, 129$ and 200 MeV/c, respectively.

the calculations of the electromagnetic dissociation contribution for such ions should take into account both of the considered mechanisms.

The photoabsorption scenario is very different for heavy nuclei, gold and lead. In this case neutrons are the most abundant particles produced in the electromagnetic collisions of ultrarelativistic nuclei [4]. When a heavy

nucleus absorbs photons in the Giant Resonance region, $6 \leq E_\gamma \leq 30$ MeV, the evaporation model may be used with the assumption $E^\star = E_\gamma$ which leads to the emission of one or two neutrons.

On the other side of the equivalent photon spectrum, when E_γ reaches the value of several GeV, the multiple pion photoproduction on intranuclear nucleons becomes the main absorption mechanism. In this case up to 95% of the photon energy is released in the fast particles on average. Nevertheless, the remaining energy deposited in the residual nucleus is sufficient for evaporating many neutrons or even multifragmentation [8]. As it was found in Ref. [4] for PbPb collisions at SPS ($158A$ GeV beam) and LHC ($2.75A + 2.75A$ TeV beams) the mean neutron multiplicities are 4.2 and 8.8, respectively. The same value for AuAu collisions at RHIC ($100A + 100A$ GeV) is equal to 7.2.

The neutron multiplicity distributions are shown in Fig. 2. They are strongly peaked at the single neutron emission channel due to GDR decay, while there is a long tail of the multiple neutron emission originating from high excitations. These results provide important information for designing large-rapidity detectors and zero-degree calorimeters at RHIC and LHC.
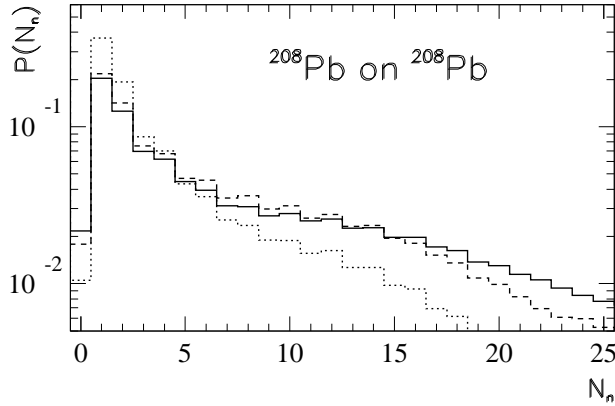

Figure 2: RELDIS predictions for multiplicity distributions of neutrons in the electromagnetic dissociation of Pb nuclei at LHC and SPS energies (solid and dotted lines, respectively) and Au nuclei at RHIC energies (dashed lines).

3   Charge changing reactions at SPS

CERN SPS accelerator currently supplies the highest energy available for heavy ion studies. A detailed understanding of fragmentation mechanisms at SPS energies provides an important point for the extrapolation of the theoretical and experimental results to RHIC and LHC energies.
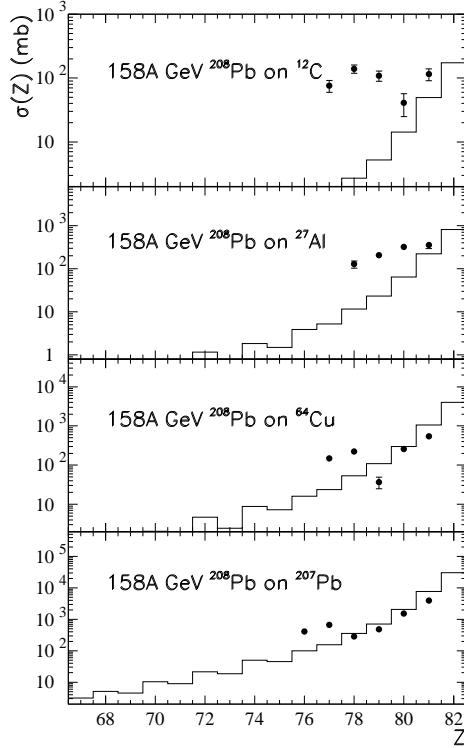

Figure 3: RELDIS results for fragmentation charge changing cross sections of ^{208}Pb ions at SPS. Points: experimental data [10].
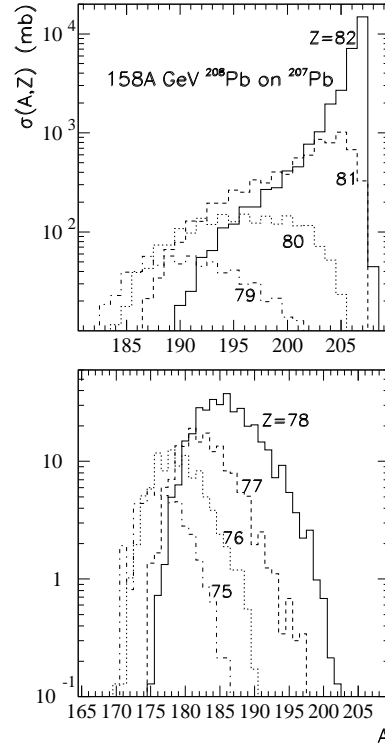
Figure 4: RELDIS predictions for mass distributions of isotopes with charges $Z = 75, 76, ..., 82$ produced in the electromagnetic dissociation of ^{208}Pb ions at SPS.

Partial break-up charge changing cross sections ($-7 \leq \Delta Z \leq 1$) for 158 AGeV ^{208}Pb ions interacting with various targets, from H to Pb, were measured recently [10]. Although the contributions to fragmentation due to the electromagnetic and nuclear forces were not separated in the experiment [10],

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one can use RELDIS code to evaluate the role of the electromagnetic dissociation for each particular dissociation mode. As it is shown in Fig. 3, the main part of charge changing cross sections in PbPb collisions may be explained by the electromagnetic interaction.

Calculations show that multiple neutron emission also plays a role in each of the partial charge changing channels with $\Delta Z = -6, ..., -1$ for PbPb collisions, see Fig. 4. The lost of each proton is accompanied with a high probability by the multiple neutron emission. For example, up to 20 neutrons may be emitted in $\Delta Z = -2$ fragmentation channel, and the emission of 8–10 neutrons is the most probable process.

This is evident from the fact that due to a high Coulomb barrier of Pb nucleus, photoemission of protons takes place well above the GDR region, particularly in the region of quasideuteron absorption, where the excitation energy, $E^\star \sim 20 - 50$ MeV, is sufficient to evaporate many neutrons. On the contrary, the mass distribution for $\Delta Z = 0$ channel is completely different since in this case $1n$ and $2n$ emission in GDR region strongly dominates. However, a long tail of the multiple neutron emission also exists in this channel.

Our expectation of the intense neutron emission in the charge changing electromagnetic collisions of heavy nuclei is very different from a simple picture assumed in Ref. [11], where the rates of neutron and proton emission above the photoproton threshold were determined by N/Z ratio of the nucleus which undergoes fragmentation. A detailed understanding of the fragmentation mechanism may be obtained by measurements of fragment masses and detection of neutrons produced in collisions of ultrarelativistic heavy ions.

4   Conclusions

A variety of fragmentation mechanisms takes place in the electromagnetic dissociation of ultrarelativistic heavy ions, namely the coalescence, Fermi break-up, evaporation, fission and multifragmentation. A partial or complete disintegration of the colliding nuclei is possible despite the absence of geometrical overlap of the nuclear densities. Comparison with CERN SPS data on PbPb collisions demonstrates the dominance of electromagnetic dissociation in the partial charge-changing fragmentation channels with $\Delta Z = -6, ..., -1$. RELDIS model predicts also a very intense neutron emission in such channels.

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